

PRACTICAL PROBLEMS INVOLVING PHASE NOISE MEASUREMENTS

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Abstract

RADAR systems, secure communications, space-based applications, precision navigation, and computer timing applications are among some of the increasingly large number of modern electronic systems with phase noise performance requirements. Making these measurements is not always as easy as using the ubiquitous multi-meter. The topology or measurement configuration can significantly impact the speed, level of accuracy, and noise floor of the measurement itself. Careful attention must be paid to many different details in order to ensure the best possible and most accurate measurement. The inherent presence of various noise types and the interaction of amplitude and phase noise can cause a user, who blindly characterizes signals, to possibly misrepresent or misinterpret the performance and other issues.

A survey of various phase noise measurement techniques is presented with their associated qualities. A few specific measurement requirements are shown with examples of actual measurements in order to illustrate current technology capability. Drawbacks of various configurations, as well as typical "gotchas," are mentioned.

INTRODUCTION

Advances in the performance of personal communication systems, as well as precision navigation and others areas, have continued to demand more stable and quieter systems. Phase noise, amplitude noise, and Allan deviation are the three common terms used when talking about the performance of a highly stable, low noise system. Understanding these areas and the different ways to use the tools is very key. Different analysis approaches and tools can be used to characterize various behaviors of a system and, thus, help in the development and integration of their performance. The phase noise measurement portion alone is large enough that this paper focuses on just a few of the key phase noise measurement typologies and reviews their advantages and disadvantages. Finally, a variety of reminders and "gotcha's" are discussed.

SINGLE-CHANNEL MEASUREMENT SYSTEM

The single channel measurement system refers to the fact that only one channel comes out to the FFT or spectrum analyzer. Figure 1 illustrates such a system. This system topology typically refers to a two-source system where one signal is phase-locked to the other. This technique is generally used when two sources, at the same frequency, are involved. This approach works over a large frequency range and has a

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reasonably low phase noise measurement floor. With only two different mixers it is possible to measure the noise on carriers from 1 MHz to 18 or 26 GHz. This is one of the simplest systems to set up and start using. Although this approach is good for measuring some of the better oscillators, one does have to worry about PLL effects close to the carrier when measuring noisy sources. If one has a very unstable oscillator, a lot of PLL gain is required to capture and hold the device in quadrature. The large amount of gain necessary to hold the wild source in lock can show itself in the phase noise plot. This is generally seen by a roll off of the noise as one approaches zero Hz offset. One of the other disadvantages is that one cannot separate the noise in the reference from that in the DUT. Multiple measurements may be required to determine which source dominates the noise floor. If the reference is 20 dB below the noise of the DUT, then the reference can be ignored and the DUT is the main contributor. If the DUT and reference are at the same level, then divide the noise between the two sources — subtract 3 dB. The three-cornered-hat method may be employed to find the best source. One must also make sure that enough averages have been taken on the FFT or spectrum analyzer for the confidence interval being reported. This is discussed in more detail below.

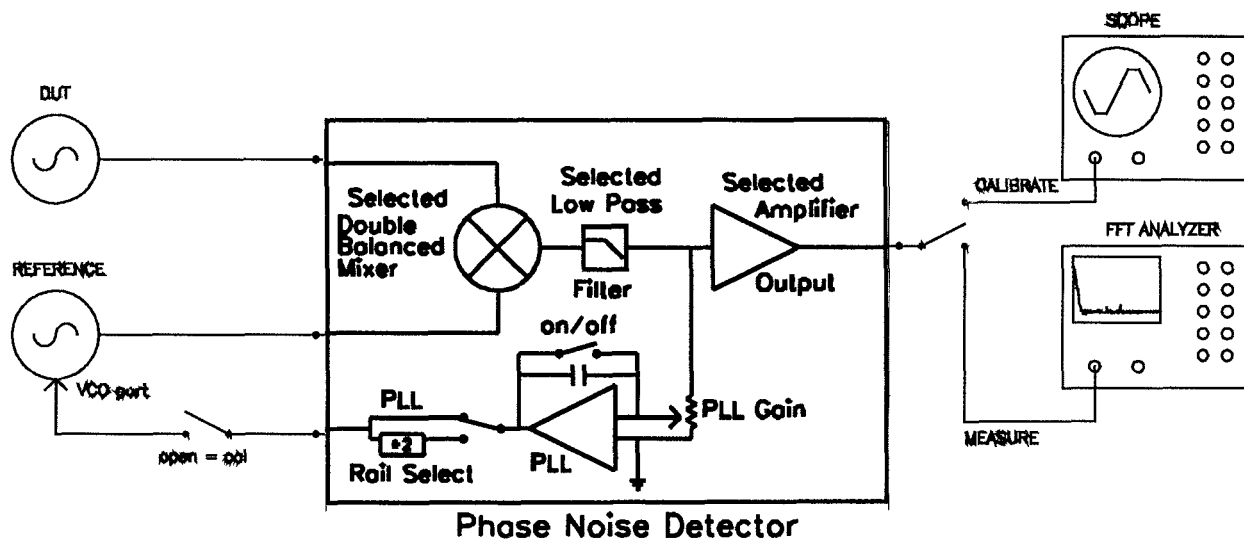


Figure 1: Single Channel Phase Noise Measurement Setup

DELAY LINE DISCRIMINATOR

The delay line discriminator technique is similar to the single-channel system except that only one source is used. Figure 2 illustrates a typical configuration. The source is usually amplified and then fed into a directional coupler. The through path of the directional coupler drives the long length of delay line. For our illustration, we used +23 dBm out of the amplifier and 500 ns of delay cable. This is typically about 350 feet or so of cable or around 10 dB of attenuation. The coupled signal is attenuated 10 dB in the coupler and fed into the phase shifter. The through path loses about 1 dB in the coupler, then about 10 dB in the delay line. The resultant is about +12 dBm on both sides of a +7 dBm mixer, which turns it on hard. This produces the best phase noise measurement sensitivity. This technique gives $S_y(f)$ instead of $S_\phi(f)$. In order to convert, one must divide by f^2 , the offset frequency at which the measurement is being made, and correctly calibrate the mixer sensitivity. The carrier frequency is then shifted up and down from center frequency an amount that produces about $\pm 1V$ change from 0 at the output of the phase noise detector. The total delta in frequency, with the total delta in voltage change, gives the mixer sensitivity adjustment.

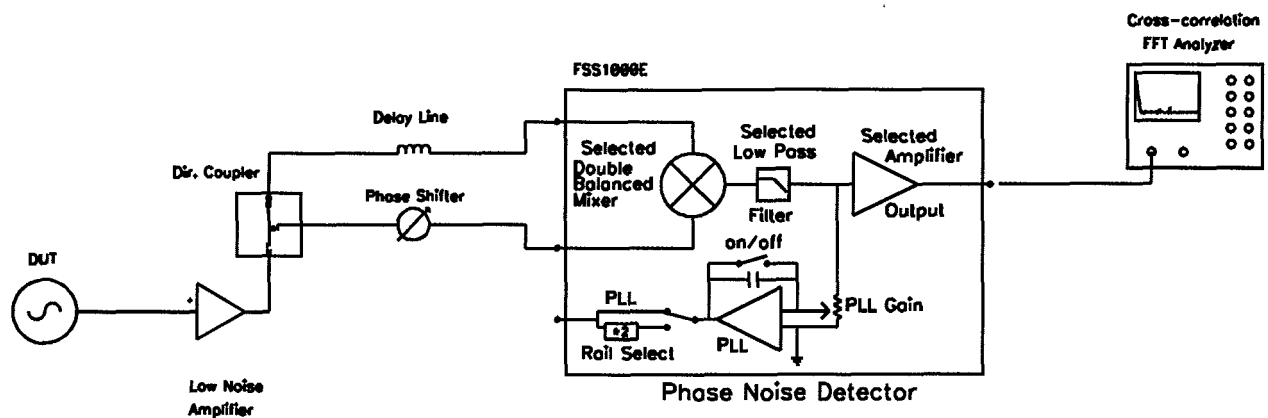


Figure 2: Delay Line Discriminator Configuration

One of the advantages is the fast measurement setup time. Since the system is put into quadrature using the delay line, no PLL is invoked. This system configuration is best for noisy sources. The fast PLL is not used; instead, the system tracks the noisy oscillator. The long delay partially decorrelates the noise from one side from the noise on the other, thus making it possible to make the measurement. Adding an amplifier inside the loop significantly raises the noise floor. That is why so much power must be present at the input. The downside is that the solution is fairly narrow band. Multiple delay lines are required for large offset frequencies and in order to cover a large carrier frequency range. Losses in the cables and the frequency coverage of the coupler and amplifier are limited. There is also a null that occurs at the offset frequency $f = 1/\tau$. It is typically recommended that a delay line be used to $1/(4\tau)$. For our example of 500 ns, one would use it from dc to 500 kHz. Details can be found in the references. The noise floor of the system is dependent upon the length of delay. Longer delay means lower noise floor, but higher loss and lower offset frequency. There is ultimately a balance point between the cost of the cable and the loss through the cable of a given noise floor and delay length. The delay line discriminator approach, while it does not involve the trickier PLL topology, it is much higher in noise than the two-oscillator approach. See Figure 6 for a comparison of the noise floors.

CROSS-CORRELATION

The cross-correlation measurement system is similar to the two-oscillator system, except that there are three oscillators. Figure 3 illustrates a typical configuration. The noise from the first reference feeds into the first phase noise detector and ends up on channel 1 of the FFT analyzer. The noise from the second reference shows up in the second phase noise detector and in channel 2 of the FFT. The DUT noise goes into the high isolation inductive power splitter and then into each of the two phase noise detectors and into both channels of the FFT analyzer. When the analyzer is set to average, the common noise is kept, and the noise not common to both channels is averaged away. This approach is more complex, requires more equipment, and is therefore more expensive. One typically achieves an improvement of 15 to 20 dB over the two-oscillator noise floor. Another way of looking at this is that the reference noise is reduced by 15 to 20 dB. This enables one to measure new devices that are better than anything else (up to 15-20 dB better

than the references). This advantage means that one can make a clear measurement of a source and know that the measured noise is the DUT.

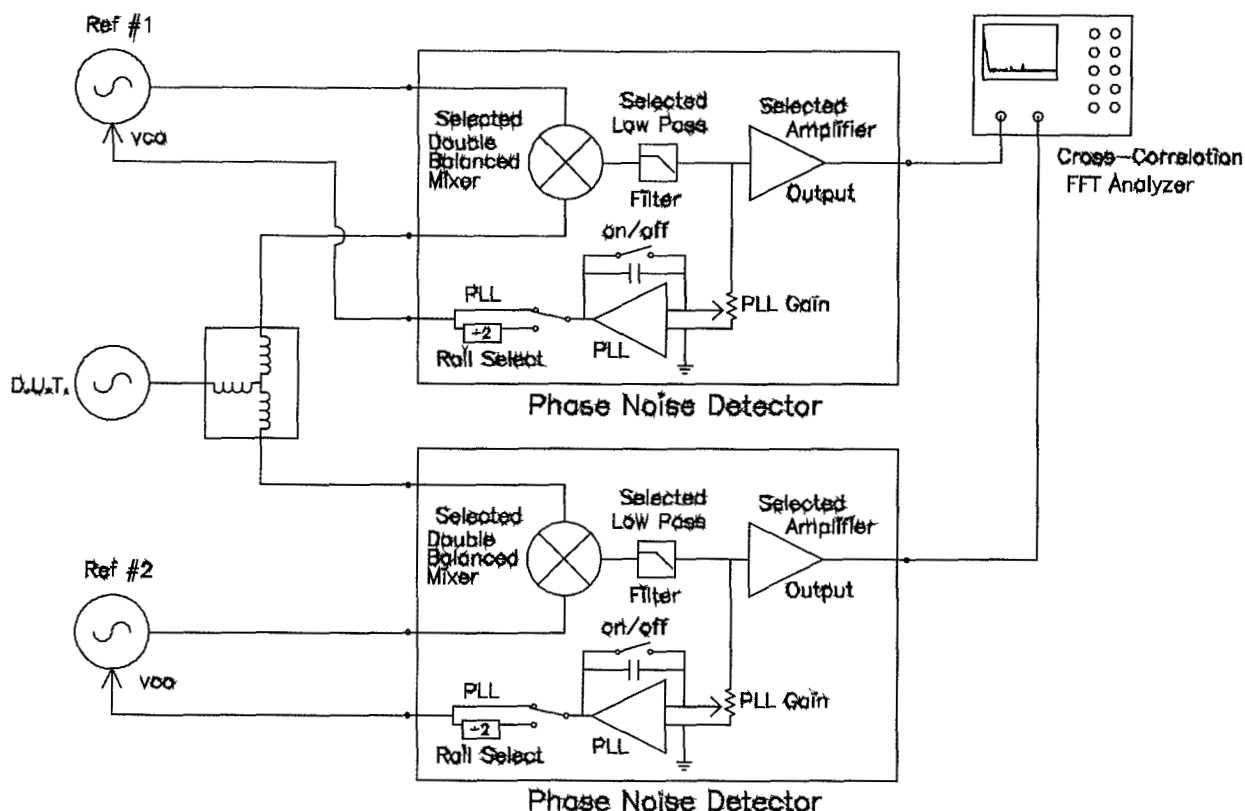


Figure 3: Cross-Correlation Phase Noise Measurement System

Like the two-oscillator method, the PLL is used in this approach to keep the sources in quadrature at the mixer. Typically one uses the cross-correlation approach for the best sources and, therefore, keeping them locked is not as difficult. Each reference is locked to track the DUT. PLL bandwidth does need to be monitored. Corrections for PLL bandwidth works to some degree, but deep corrections have growing errors.

Since the noise of the uncorrelated inputs is being averaged away, many more averages are required to achieve the same confidence interval. Just like the two-oscillator method, and unlike the basic delay line discriminator, this system can be used over a large frequency range without changing a lot of hardware. The delay discriminator system can be extended using a front-end down conversion, say to 100 MHz, and then the rest of the amplifier and loop section is always done at 100 MHz. Cross-correlation can also be added to the delay discriminator solution to improve the noise floor by 15 to 20 dB.

"GOTCHAS"

There are many areas in which one can be tricked into false readings or frustrated with the process of trying to achieve a good measurement. Some of these areas are touched on in this section.

PHASE NOISE STANDARD

Some of the simple calibrations work well when one understands that the rest of the system is well behaved. Most of the time this is acceptable. Sometimes it is necessary to look at an entire system's performance including the PLL. The AM/PM Calibration Standard allows one to inject a known amount of phase noise onto a signal and look at how this transfers through the system. How the system reports the final number can be compared to how the noise was put onto the carrier and a correction for the system can be determined for all offset frequencies being used. Figure 4 Illustrates the typology of the system and Figure 5 shows a typical resulting plot. The flat line at the top of the plot illustrates the calibration level and flatness of the measurement. The regular noise plot at the bottom is the calibrated noise measurement. This one plot then encapsulates the entire performance of the system including the end results.

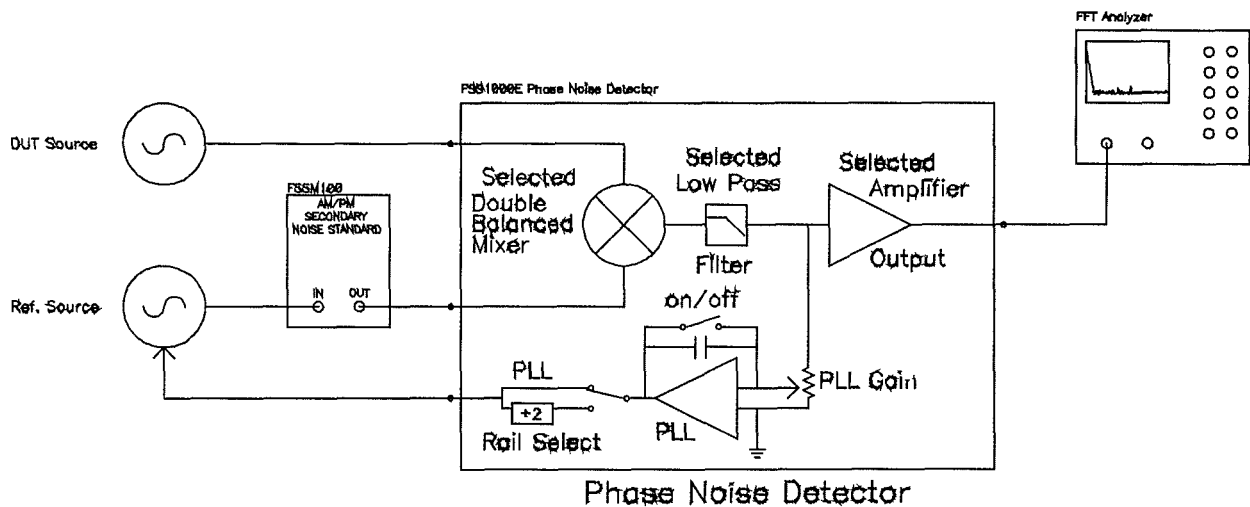


Figure 4: Single Channel System With Noise Source

INJECTION LOCKING

Injection locking occurs when the system appears to phase lock itself without the help of the PLL. In this case, control of the system is lost to some extent and true quadrature is not guaranteed. The noise of the sources is also cleaned up due to the injection lock; therefore, the resultant measurement is biased. Injection locking can occur through the power supplies, through the air, and through the mixer itself. Microwave sources in particular, but also sources that are not shielded properly will phase-lock through the air. One can place a large glass of water in the area and watch the system change. The water absorbs some of the radiation from the sources and changes the lock. Power supplies must have good isolation and the sources must have good isolation to the mixer. Sometimes low noise isolation amplifiers must be used to prevent the sources from locking through the mixer.

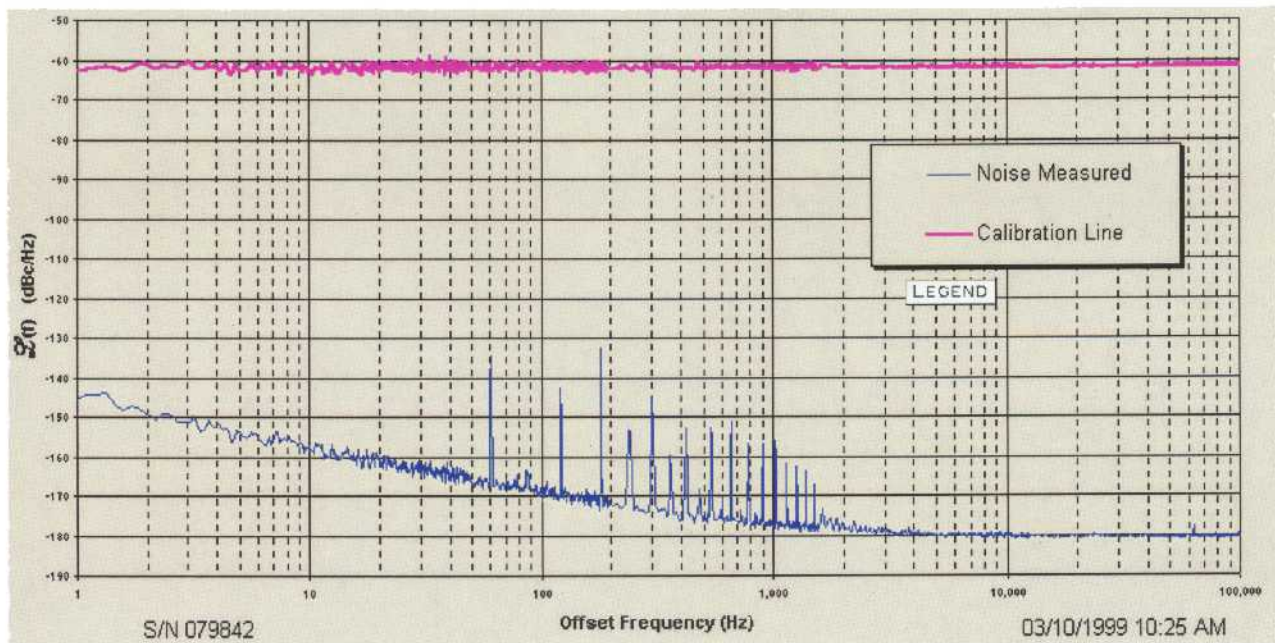


Figure 5: Graph of Single Channel System With Noise Source

If a system is set up to measure the beat note between the two sources, the duty cycle of the beat note is an indicator of injection lock. If the beat note is between 45% and 50% duty cycle, then everything is probably acceptable. If the duty cycle is quite a way from 50% duty cycle, the sources are trying to injection-lock through the mixer. One can also increase the beat frequency before closing the PLL loop.

NUMBER OF AVERAGES

The number of averages taken can make a big difference on the confidence interval on the data. If one takes only four averages, the 95% confidence interval has an error margin of -3 to $+6$ dB. This is a 9 dB error window. Often people take too few averages and then report a number like -145.23 dBc/Hz. The 0.23 dB portion simply does not matter when you have a 9 dB error window. Table 1 illustrates the relation between the number of required averages and the error window for a given confidence interval.

SELECTING THE RIGHT TOPOLOGY – SYSTEM SUMMARY

There are many different possible ways to configure a system for a phase noise measurement. One a few of the main approaches were discussed above. Each of these systems can be changed into a hybrid configuration. For instance, delay line discriminator with carrier suppression is a combination of two of the systems. The key then is to take the knowledge of the different systems and match the best system approach to the measurement requirements that need to be met. A summary of each of the systems discussed is shown below.

Number of Samples	$k \cong 1$ (approx. 68%)			$k \cong 1.9$ (approx. 95%)		
	$S_m = S[1 \pm \Delta]; S = S_{mL,H} + \text{dB}$			$S_m = S[1 \pm \Delta]; S = S_{mL,H} + \text{dB}$		
	Δ	S_{mL}	S_{mH}	Δ	S_{mL}	S_{mH}
4	0.54	-2.0	+3.3	2.5	-3.0	+6.0
6	0.42	-1.5	+2.3	1.4	-2.5	+5.0
10	0.32	-1.2	+1.7	0.61	-2.1	+4.0
30	0.18	-0.72	+0.86	0.35	-1.3	+1.8
100	0.10	-0.41	+0.46	0.19	-0.76	+0.92
300	0.058	-0.24	+0.25	0.11	-0.46	+0.51
1000	0.032	-0.13	+0.13	0.06	-0.26	+0.28
3000	0.018	-0.08	+0.08	0.035	-0.15	+0.15
10000	0.010	-0.04	+0.04	0.019	-0.08	+0.08

Table 1: Error Window vs. Number of Averages for a Given Confidence Interval

Single-Channel Tw- Source Method (See Figure 1)

Uses two sources – one reference, one device under test
 PLL used to keep both sources in quadrature at output of mixer
 PLL bandwidth can bias data close to the carrier
 Lower noise floor than delay line discriminator approach
 Low cost to implement and broad frequency coverage with few components
 Can be difficult to determine which source or system floor dominates
 See Figure 6 for a typical system noise floor plot

Delay Line Discriminator (See Figure 2)

Uses one source and a long length of delay cable
 Works better with noisy sources
 Quadrature achieved using a phase shifter
 No PLL bandwidth attenuation to worry about
 Requires more components than Single-Channel Two Source Method
 Higher Noise Floor than Single-Channel Two-Source Method
 Faster to setup than most other methods
 See Figure 6 for a typical system noise floor plot

Two Channel Three Source Cross-Correlation (See Figure 3)

Uses three sources – two references, one device under test
Typically 15 – 20 dB lower noise floor than Single-Channel Two-Source Method
Can measure sources that are better than the device under test
More equipment required; including cross-correlation FFT analyzer
PLL used to keep sources in quadrature at output of mixer
PLL bandwidth can bias data close to the carrier

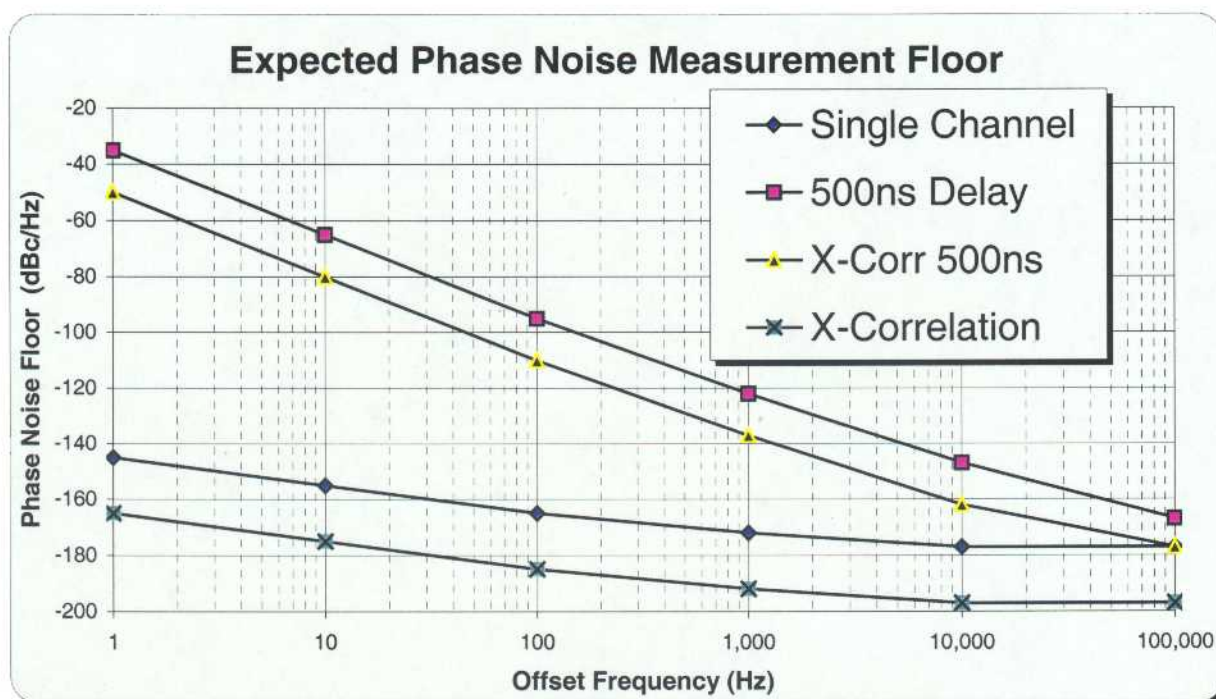


Figure 6: Comparison of the Noise Floor for Several Different Configurations

GOTCHA SUMMARY

Listed here is a quick survey and summary of some of the areas that many people run into problems and some possible solutions. Keeping these items in mind when one is trying to configure a measurement system may help to reduce measurement frustrations.

Problem:	Reference noise compromises measurement.
Fix:	Obtain lower noise reference or use cross-correlation and two independent references.
Problem:	System noise compromises measurement.
Fix:	Use higher drive levels and/or higher drive level mixer.

Problem:	Broadband okay, but $1/f$ region too high.
Fix:	Look at a better reference or use carrier suppression or replace mixer.
Problem:	System overall noise floor is too high.
Fix:	Change over to a cross-correlation topology.
Problem:	Calibration has errors due to mixer/amplifier gain variations with offset frequency.
Fix:	Use an AM/PM calibration standard to measure the system at each offset frequency.
Problem:	Residual detection of AM noise from Ref or DUT compromises measurement.
Fix:	See if a mixer with better balance will solve the problem or try to inject AM on the signal and adjust the phase balance (dc offset in the PLL loop) to minimize AM detection or switch to carrier suppression.
Problem:	Injection locking is occurring.
Fix:	Improve the isolation between the sources and the mixer either by using an attenuator or an isolation amplifier. One may also need to look at power supplies or shielding.
Problem:	PLL bandwidth compensating for the phase noise close to the carrier.
Fix:	Reduce the PLL gain or switch to the delay line discriminator approach or measure the amount of attenuation and compensate. This can be done using an AM/PM calibration standard.
Problem:	PLL doesn't seem to be locking.
Fix:	Do you have the right tuning voltage for your PLL output matched to the tuning range of your source? Does the source tune far enough to match the frequency of the other source? An external bias to the tune might be necessary to get the source close to the desired operating frequency.
Problem:	PLL still doesn't seem to work.
Fix:	Frequency-divide the sources to a much lower frequency. Since the phase excursion also is divided, much less PLL gain is required and, hence, the PM bias is much less.
Problem:	The final plot has large excursions between the peaks and valleys.
Fix:	If you don't have a fairly fine line through the noise sections of the plot, the number of averages needs to be increased. See Table 1 for details.
Problem:	Line harmonics are too high or causing excess measurement noise.
Fix:	Make sure all of the equipment is on the same side of the ac line. Look at using line filters, conditioners, or batteries. Consider using an inside/outside dc block. Move the measurement system away from high ac current sources and transformers.

CONCLUSION

Characterizing the phase noise of a system or component is not necessarily very easy. Many different approaches are possible, but the key is to find the best approach for the measurement requirements at hand.

A survey of some of the more common topologies along with some possible trouble spots helps one to review and keep in mind the advantages and limitations of each approach.

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